TETA TO-0022
August 27, 1993
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TEST EFFECTIVENESS TREND OBSERVATION

EMI Anomalies Encountered Prior to Acceptance Testing

CONCLUSION:

A review of the PFRs from 5 flight projects revealed that 70 percent of the EMI problems were related to common mode current effects. Moreover, a large number of these anomalies were identified during developmental testing. These results indicate (1) that early EMI developmental testing is beneficial for identifying EMI problems prior to the fabrication of flight hardware and (2) that the addition of common mode conducted emission tests, bulk current injection tests, and AC isolation tests could be effective in identifying these as well as other types of EMI problems.

BACKGROUND:

Electromagnetic Compatibility (EMC) in spacecraft is concerned with the generation, transmission and reception of electromagnetic energy in a manner which does not result in anomalous behavior of the spacecraft or its payload.

In the testing of spacecraft systems for electromagnetic compatibility a series of tests generally are performed based on standard requirements, such as the GSFC GEVS -STS, the MSFC 521-B, and MIL-STD-461/462. The main EMC tests performed are conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility. Some DC magnetic characterization measurements may be included. Appendix A contains a very brief description of these tests.

Typically, EMC acceptance testing is performed late in the program as part of the final environmental qualification. Correcting problems discovered this late in the program usually involves costly retrofits with adverse schedule and cost impacts. Alternatively, waivers to the requirements may be processed. However, waivers for non -compliance involve increased risk of in-flight anomalies. Consequently, the identification of EMC concerns in the flight hardware early in the development phase generally has less programmatic impact and is more cost effective.

Recently, two new EMC tests have shown promise for identifying potential EMI problems: a) common mode conducted emissions, and b) bulk current injection (BCI). Common mode conducted emission tests are presently being implemented in developmental testing of some assemblies for the Cassini spacecraft. Bulk current injection testing is currently used in industry and by some DOD agencies but has not been implemented at JPL or other NASA Centers.

DISCUSSION:

The focus of this study is on the one of a kind spacecraft which have launch constraints. These spacecraft do not have the benefit of a test history developed over time during testing multiple spacecraft in series such as the NOAA and TIROS Programs. Furthermore, the spacecraft must be ready when the launch window opens or a delay in the launch date of from 1 to 2 years may be necessary.

The objectives of this analysis were to assess the nature of EMI problems encountered during the developmental and fabrication phases and to identify the types of EMC tests which would be useful in reducing EMI anomalies in spacecraft assemblies. This study involved the last five (5) spacecraft built or managed by JPL: Voyager, Galileo, Magellan, Mars Observer, and Topex.

Initially only those EMI-related problem failure reports (PFRs) recorded during development and function al testing were examined. These PFRs were reviewed to classify the underlying EMI problems involved. Later the review was extended to include those PFRs related to EMC acceptance testing. Typically the acceptance tests are performed either on an engineering model (prototype) or actual flight hardware. The EMC acceptance tests are usually performed using a standard method (e.g. MIL-STD-461/462) and are intended to verify compliance with overall environmental requirements.

Table 1 shows the number of PFRs (for the five spacecraft) and the most typical types of EMI anomalies that were encountered during developmental/functional tests. Appendix B contains a brief description of each anomaly category represented in Table 1. Table 2 shows the number of PFRs generated during EMC acceptance testing.

In general, EMC anomalies can be categorized into two groups: a) those of a radiated nature and b) those of a conducted nature. The underlying cause for anomalies related to conducted EMI are improper shielding (i.e. cable shielding), conducted coupling, transients, and grounding. The underlying cause for anomalies related to radiated EMI are radiated coupling (electric and magnetic), RFI, and spurious emissions/undesired response. In general, anomalies that are of conductive nature are the result of common mode noise currents and associated grounding problems. Anomalies of a radiated nature are the result of field-to-wire, field-to-structure or field-to-device coupling - all resulting in the inducement of noise current. In all cases, the nature of EMI anomalies is manifested by the presence of an extraneous current (noise current) that exist in addition to the functional current. The most effective EMC tests for identifying potential anomalies in spacecraft assemblies during development would be those tests which are more efficient at detecting and measuring this noise current.

The most commonly used EMC tests using MIL-STD-461/462 for testing spacecraft assemblies are listed in Table 2. In Table 2 over 50 percent of the PFRs for conducted and radiated emissions resulted from the very stringent Space Shuttle radiated/ conducted emission requirements for payloads which were imposed on the Galileo and Magellan spacecraft.

Data acquired in early testing, during the developmental stage, can be very important as the basis for assessing the risk associated with waivers considered late in the program. Furthermore, conducted and radiated electric field emissions tests (in Table 2) are required EMC tests for hardware qualification purposes. However, their usefulness for reducing EMI anomalies in spacecraft assemblies during the developmental stages is dependent on the knowledge of how susceptible such assemblies are to emitted fields. Hence, radiated susceptibility testing is a prerequisite for making good use of radiated/conducted emissions data in engineering decisions.

The data in Table 1 indicates that approximately 70 percent of the EMI anomalies are related to shielding, conducted coupling, transients, and grounding (i.e., common mode noise problems). Thus, common mode current is a major source of EMI problems. Consequently, a "common mode conducted emissions" test is of great value for quantifying the amount of common mode conducted noise current, hence, a good test for a qualitative and quantitative assessment of possible grounding problems. Appendix C describes this test in some detail.

Because field-to-wire coupling is so prevalent in many EMI situations, a "bulk current injection" test would provide essential data to assess worst-case coupling to sensitive assemblies. This technique provides an efficient means of injecting RF currents into individual cables or cable bundles. When used in conjunction with a radiated susceptibility test, it can facilitate the separation of radiated susceptibilities into cable problems and enclosure defects. Appendix D describes this test in some detail.

Both of the suggested tests have the additional advantage of easy implementation, especially during the bench testing of assemblies. Neither test requires a special EMC chamber (e.g. shielded room or anechoic chamber) and the amount of equipment for performing the tests is minimal.

Grounding related problems are a major source of test failures, particularly in the case of RF noise. While 17% of the developmental and fabrication PFRs are directly related to grounding, grounding is also a factor in many of the PFRs described as shielding problems. Although the conventional DC isolation test (in Table 2) can provide assurances of single point grounding and the separation of digital and analog ground paths, its usefulness is limited for detecting of RF/MW grounding problems. Determination of the RF impedance to ground requires an additional test element to include the frequency dependent parameters C and L. Based on the high incidence of grounding related anomalies, it appears warranted to include an AC impedance measurement as part of the isolation test procedure for identified circuit interfaces.

By comparing the results of Table 1 with the different types of tests outlined in Table 2 we can conclude the following:

1) conducted susceptibility tests (including transient tests) can provide a good indication of how susceptible an assembly is to common mode current effects as well as grounding problems, hence, conducted susceptibility test data are essential in analyzing the EMI problems related to improper shielding, conductive coupling and transients reported by the PFRs in Table 2.

2) radiated susceptibility tests can provide a good indication of how susceptible an assembly is to field-to-wire, field-to-structure, field-to-device, and RFI types of coupling, hence, radiated susceptibility test data are essential in analyzing the EMI problems related to radiated coupling, RFI, and spurious/undesired response indicated by the PFRs in Table 2.

3) In the special case of spacecraft instruments which measure (or are very sensitive to) magnetic fields, their threshold of susceptibility to such fields is usually well known. DC and radiated magnetic tests on assemblies which may be suspect of emitting "magnetic noise" can provide a good indication on how susceptible magnetic sensitive instruments are to field-to-wire, or field-to-instrument coupling, hence magnetic tests are useful in analyzing EMI problems related to magnetic radiated coupling as indicated by the PFRs in Table 2.

In conclusion, the review of the PFRs for the 5 spacecraft studied has identified 367 EMI -related problems which were addressed prior to the start of formal EMC acceptance testing. Early identification of these problems provided opportunity for implementing design changes or corrective measures without the adverse impacts of schedule delays and costs late in the program when the formal EMC acceptance testing is normally performed. The implementation of additional EMC type testing during the developmental phase would provide increased opportunity to implement corrective design changes prior to the fabrication of the flight hardware.

Table 1. Number of PFRs for EMI-related anomalies during developmental and fabrication testing of spacecraft assemblies

Spacecraft	*Improper Shielding*	*Conducted & Radiated Coupling*	*Spurious Emissions & Undesired Response*	*RFI*	*Transients*	*Grounding*
Voyager	40	24	13	8	11	21
Galileo	61	15	8	7	9	13
Magellan	6	1	4	2	4	3
Mars Observer	24	10	4	2	4	16
Topex	21	11	4	6	6	9

Table 2. Number of PFR`s during EMC Qualification testing (MIL-STD-461/462).

Spacecraft	*Conducted Emissions*	*Conducted Susceptibility*	*Radiated Emissions*	*Radiated Susceptibility*	*Magnetics*	*Isolation*
Voyager	14	6	18	10	17	10
Galileo	38	9	62	16	12	9
Magellan	13	0	6	6	3	0
Mars Observer	9	4	14	8	0	1
Topex	14	9	18	7	0	2

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APPENDIX A

Electromagnetic Compatibility Tests: Brief Description

Conducted Emissions: The intent of the conducted emission requirements is to restrict the AC noise current passing out through the spacecraft assemblies' power/signal cables. The reason for this is that these noise currents will be placed on the common power/data bus of the spacecraft and can affect other systems and instruments which feed from the same power/data bus (conducted EMI).

Radiated Emissions: The intent of the radiated emissions requirements is to restrict the unintentional radiated levels of electric and magnetic fields that are produced by any spacecraft system, subsystem or instrument. The rationale for this is that these emissions can interfere with the spectrum of many receiver circuits. Furthermore, these levels of emissions can "couple" to many types of conductive paths (e.g. wires, cables, ground bus...etc.) causing significant interference to susceptible electronics.

Conducted Susceptibility: Spacecraft electronic systems can be susceptible to a wide variety of interference signals that enter via DC power and signal cables. Example of such interference are: a) electrostatic discharges, b) conducted noise from switching power supplies, d) transient spikes, and e) noise coupling to cables from externally generated fields (both intentional and unintentional field sources). The objective of these tests is to verify that noise entering power and signal cables will not interfere with the normal operating conditions of spacecraft systems.

Radiated Susceptibility: The purpose of this test is to ensure that the spacecraft system, subsystem and instrument will operate properly in an environment where intentional and unintentional radiators of electromagnetic energy are present. The objective of these tests is to verify that electric and magnetic fields generated within the spacecraft environment are not going to interfere with the normal operating conditions of spacecraft electronics.

Grounding: The objective of this test is to verify that power circuits are isolated from chassis ground or circuit common according to given specification requirements. The chassis of all spacecraft systems must be grounded to a single point (single point grounding) in order to avoid EMI grounding problems such as: a) ground loops, b) common impedance coupling.

For those circuit interfaces where RF grounding is of concern, measurement of the inductance and/or capacitance to ground is of importance.

Magnetic Characterization: The intent of the magnetic characterization, or mapping, is to measure the magnetic dipoles (i.e. dipole moment) of spacecraft assemblies and investigate how the magnitudes of such dipoles can interfere with magnetometers, plasma wave devices, and other instruments that may be sensitive to ambient magnetic fields.

APPENDIX B

Underlying Cause of Common EMI Anomalies in Electronic Subsystems

Improper Shielding: Improper shielding refers to shielded cables or enclosures that suffer from a variety of deficiencies: 1) shield in cables shorted/broken, 2) shield in cables connected at the wrong location, 3) bad shield connections (i.e. connections have high resistive values) 4) shielded enclosures for sensitive electronics is improperly connected...etc. The results of these deficiencies are severe degradation in performance as a result of common mode currents and/or grounding problems.

Radiated/Conducted Coupling:

Radiated Coupling: Radiated coupling refers to RF/MW radiated energy coupling into sensitive electronics and cables. This is known genetically as field -to-cable coupling. The radiated energy can originate either from within the assembly itself (intrasystem incompatibility) or from another source (intersystem incompatibility). The effects consist in a degraded performance as a result of strenuous induced currents.

Conducted Coupling: Conducted coupling refers to presence of conducted noise current which has coupled, through a conductive path, into a sensitive electronic device. Common mode currents and grounding deficiencies are the main source of conducted noise. Degraded performance or non -performance are the results of such anomalies.

Spurious emissions/response: Spurious emission is any electromagnetic emission of a transmitter outside its intended emission bandwidth. Receiver spurious response is any response of a receiver to a signal outside its intended reception bandwidth. The resulting anomalies are typical of transmitters and receivers.

Radio Frequency Interference (RFI): RFI occurs when a signal(s) or intermodulation products from the unintended transmitter fall within the intended bandwidth of a receiver. The resulting anomalies are also typical of transmitter and receivers.

Grounding: Grounding refers to the three different kinds of grounding problems that can be present on an electronic system: a) common impedance coupling, b) unintentional ground paths, and c) ground loops. Grounding anomalies can seriously deteriorate the performance of an electronic device.

Transients: Transients refers to the either ON/OFF or unexpected surges in currents that assemblies experience. These transients result in: a) temporary increase of current in cables which can radiate and affect other sensitive electronics, b) temporary increase of conducted noise, and c) current/voltage overloads in the circuits.

APPENDIX C

Common Mode Current Testing: Brief Overview

In an ideal electronic circuit only differential current (i.e. the functional current) would be found. In an ideal 2-line circuit with a forward (+) and return (-) wire the differential mode currents are equal in magnitude but opposite in direction. These are the kind of currents used in transmission line modeling.

Common mode current is that current which flows from one of the differential current paths to ground. Common mode currents are undesired currents. They are not necessary for the functional performance of the electronic device that the lines connect. Typically, the common mode current will be substantially smaller than the differential mode currents but the effects can be serious from the EMI point of view. Common mode currents can be a major source of radiated emissions as well as the main cause of ground loops and other grounding problems in electronic devices. It can be shown that a small amount of common mode current can produce as much radiated EMI as a large amount of differential-mode current (differential-mode currents are the "functional" or desired current on a line).

Ideal models such as the transmission line model will not predict the common mode currents. A number of physical parameters, such as proximity to conducting planes and other structural asymmetries, can be responsible for the creation of common mode currents. The presence of parasitic capacitances and inductances among many types of circuit components and between electronics and ground planes allow the common mode current to follow unintended paths creating several types of conducted EMI problems including ground loops.

Figure C 1 of this appendix shows a typical set up for measuring the common mode current of an equipment under test (EUT). A Line Impedance Stabilization Network (LISN) is used to "clean up" any noise on the power bus that feeds the EUT, hence, all the noise to be measured will be generated within the EUT. In this example the common mode current is measured at the power leads of the EUT (common mode current can also exist in signal leads). Notice that in one location the current probe is connected around both the (+) and return (-) leads. The current probe will not pick up the differential mode current because such current travels in opposite direction in the two leads, hence, the magnetic field generated by the two leads cancel each other and can not be detected by the current probe. The current probe however, will detect the common mode current present in either lead or in both leads (depending on the unintended path followed by such current). As observed in the figure, the other location chosen for the current probe is around the return and ground lead from chassis. Common mode current is often found in grounded leads due to parasitic coupling.

APPENDIX D

Bulk Current Injection Testing: Brief Overview

Three new limits and test procedures in the draft revisions of MIL -STD-461C/462 use a "new" technique known as bulk current injection (BCI). BCI techniques will not only be featured in MIL -STD-461D/462 but are also featured in Radio Technical Commission for Aeronautics EMI Susceptibility Requirements RTCA/DO -160C. It is very possible that the next revision of MIL - STD-1541A, which deals with EMC requirements for space systems, will also contain BCI testing.

BCI tests use an injection clamp similar to one current probes used for conducted emissions testing. A current probe acts as a single turn primary, multiple turn secondary transformer, placing low series impedance in the probed power line or signal lead while capable of driving a usable signal into a 50 ohm receiver. A current probe is characterized by its transfer impedance Z_T (dB-ohms) defined as the ratio of the output voltage into a standard load (usually 50 ohms for EMI testing) divided by the net current traveling through the probe area. A bulk current injection clamp has similar core materials to a conventional EMC transformer but with a heavier winding and acts as a multiple turn primary and a single turn secondary transformer, when placed around a power line or signal lead. Thus it provides a nominal 50 ohms load to the susceptibility signal source, while providing lower susceptibility signal source impedance when placed in series with a cable under test. A BCI clamp is characterized by its insertion loss I_L(dB). The insertion loss describes the inefficiency of the clamp relative to direct injection into a 50 ohm circuit.

Bulk current injection is a testing technique which tends to simulate at a local level (i.e. at a specific cable and cable location) the coupling of external radiated electromagnetic fields. Radiated susceptibility testing is the technique normally used to simulate such external electromagnetic environment. BCI testing can be used to complement radiated susceptibility testing, specially when testing the susceptibility of wire bundles to RF/MW coupling. BCI is a good EMC testing technique for spacecraft assemblies where RF/MW immunity testing of cables is critical (to some specified loads) and radiated susceptibility testing of such cables is not feasible due to physical, procedural or technical constraints. Figure D1 shows a test set up for BCI of an equipment under test (EUT).

An advantage of bulk current injection is that low RF power can induce currents in wire bundles that would require very high radiated RF power to induce the same current. BCI however, is not a substitute for radiated susceptibility testing; this is due to two main reasons: a) radiated susceptibility testing tests much more than just the coupling of electromagnetic fields to cables. During such tests the fields induce currents not only on cables but also on apertures, metallic structures, and diverse types of electronics, and b) the currents induced on individual cables using bulk current injection are not necessarily the same as those induced by radiated field excitation. This is because radiated excitation include current sources distributed over the length of the cable while injection uses only a single discrete source. Only when the cables are electrically short (with respect to wavelength) similarities between the two methods may be observed. For electrically long lines, standing wave patterns are prominent, and large differences appear between the two excitation methods. That is why it is recommended that when applying this test the injection probe should be located as close as possible to the susceptible device.

As shown in Figure D1, BCI testing consists of the injection of RF noise into a cable under test (CUT) using a magnetic injection probe. The RF power in provided by a signal generator (tuned to a particular testing frequency) whose output is connected to the input of a wide band amplifier. The amplifier delivers a specified "forward" power prescribed by the specifications. A power meter is used for monitoring the forward power and a receiver (e.g. wide band oscilloscope) is used for measuring the amount of injected current at the frequency of interest. The procedure is continued through the frequency range specified by the specifications. By monitoring the power output the engineer can determine the threshold induced current in the EUT cables capable of causing EMI anomalies.

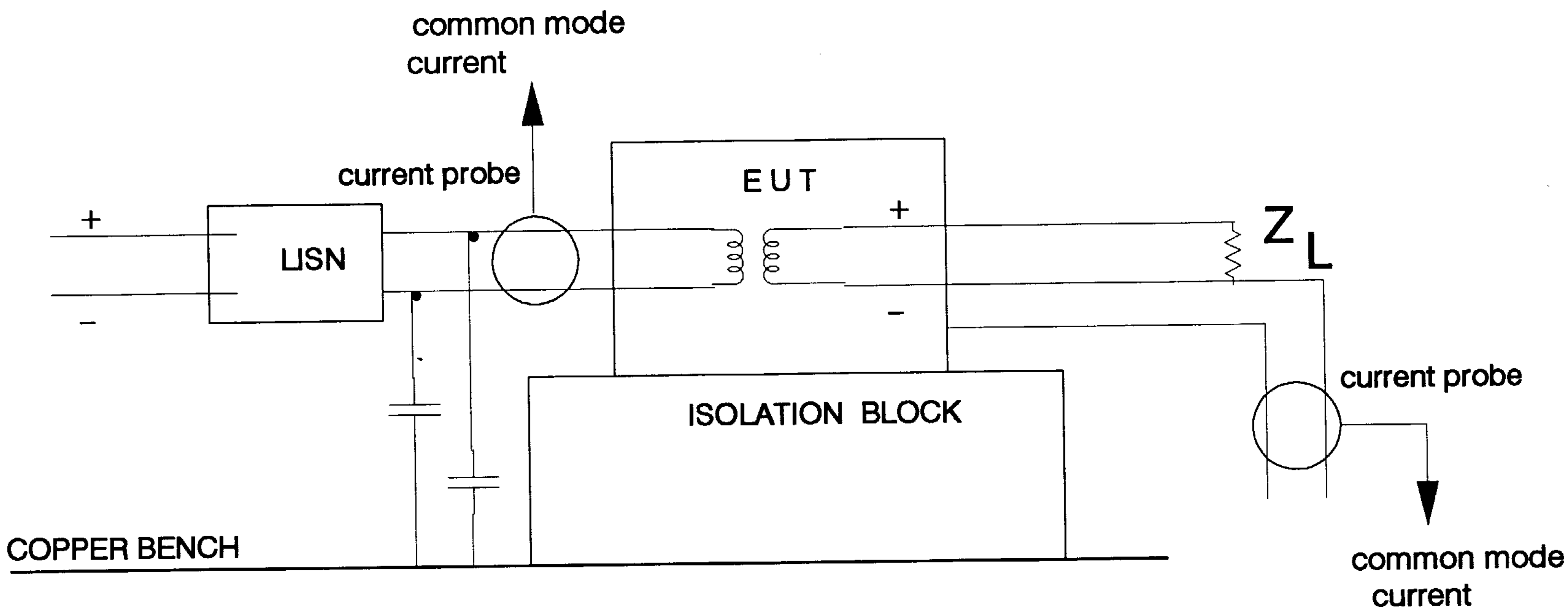

Figure C1. Performing Common mode emissions testing on power/ground leads

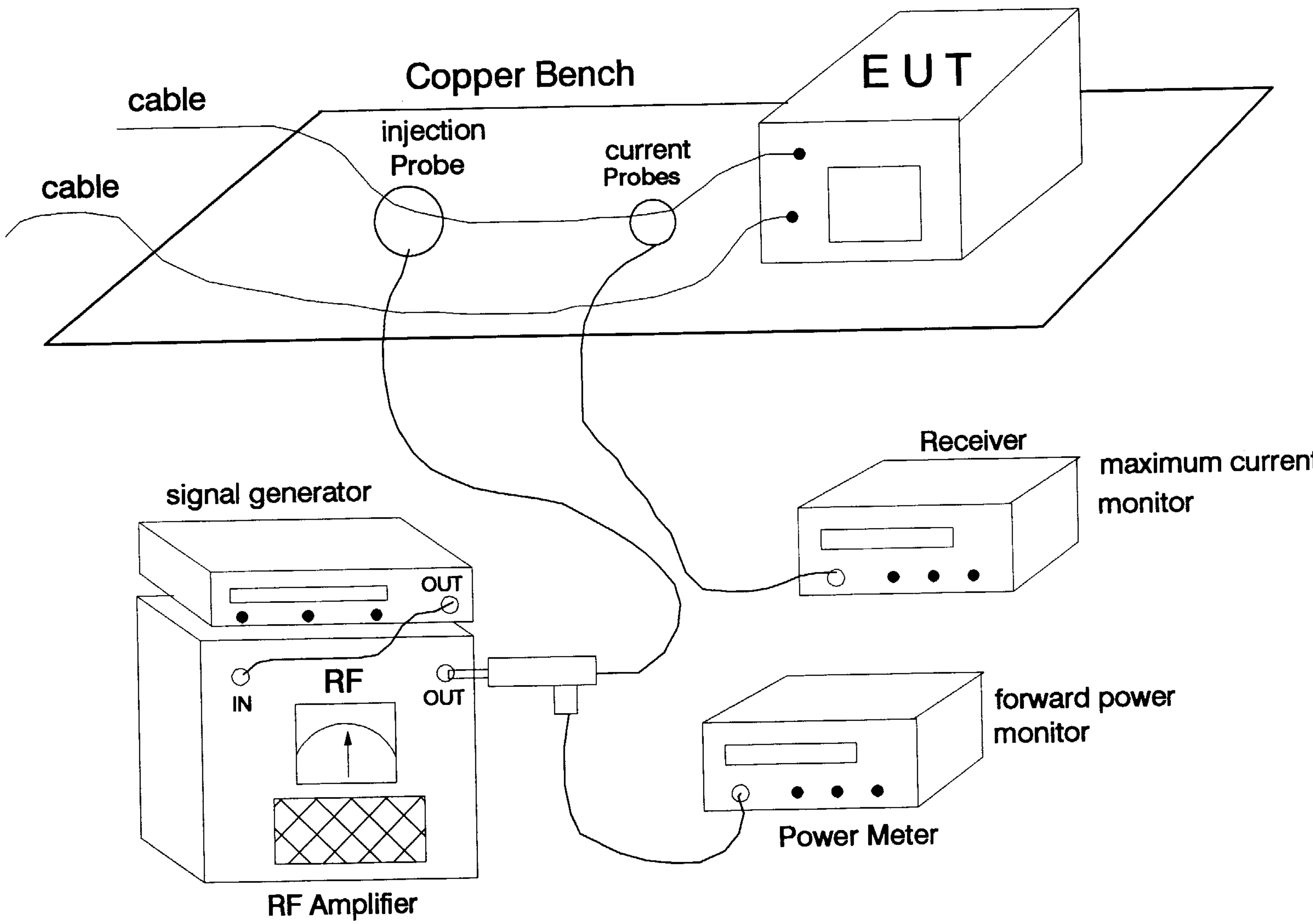

Figure D1. Bulk Current Injection Testing